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Under the support from AFOSR-DRRIP, Ultrafast Optoelectronics Lab. Rensselaer Polytechnic Institute has installed a new laser system (Spectra-Physics Ti:sapphire laser and Optical parametric oscillator) for linear and nonlinear terahertz spectroscopy. Based on the new laser sytem, they developed several novel methods to detect ultrafast electromagnetic pulses, including the first free-space electro-optic sensor for terahertz field measurement. These new sensors will impact the ultrafast electronics and photonics community. As a result, an electro-optic real-time imaging system for terahertz field application has been demonstrated.

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Summary

Under the support from AFOSR-DRRIP, Ultrafast Optoelectronics Lab. Rensselaer Polytechnic Institute has installed a new laser system (Spectra-Physics Ti:sapphire laser and Optical parametric oscillator) for linear and nonlinear terahertz spectroscopy. Based on the new laser sytem, they developed several novel methods to detect ultrafast electromagnetic pulses, including the first free-space electro-optic sensor for terahertz field measurement. These new sensors will impact the ultrafast electronics and photonics community. As a result, an electro-optic real-time imaging system for terahertz field application has been demonstrated.

Accomplishments / New Findings: We have installed a Spectra-Physics Ar ion laser pumped Ti:sapphire laser with an optical parametric oscillator. We are testing a Ti:sapphire regenerative laser amplifier. We have used our oscillator to measure the performance of regular GaAs (long carrier lifetime) THz radiation and newly developed electro-optic sensors for ultrawideband terahertz beam applications.

Publications: published and submitted journal papers supported by this grant.

1. M. Li, F. G. Sun, G. A. Wagoner, M. Alexander and X.-C. Zhang, "Measurement and Analysis of THz Radiation from Bulk Semiconductors," *Appl. Phys. Lett.* **67**, 25 (1995).
2. F. G. Sun, G. A. Wagoner, and X.-C. Zhang, "Measurement of Free-Space THz Pulses via Long-Lifetime Photoconductors," *Appl. Phys. Lett.* **67**, 1656 (1995).
3. Q. Wu and X.-C. Zhang, "Free-Space Electro-Optic Sampling of Terahertz Beam," *Appl. Phys. Lett.* **67**, 3523, (1995).
4. X.-C. Zhang and Y. Jin, "Generation of THz Radiation from Semiconductors," *Ultra-Wideband, short-Pulse Electromagnetics 2, Ed. by Carin, Plenum Press*, 17 (1995).
5. Y. Jin and X.-C. Zhang, "THz Optical Rectification," International Journal of Nonlinear Optical Physics, **4**, 459 (1995)
6. Q. Wu, M. Lize, and X.-C. Zhang, "Broadband Detection Capability of Electro-Optic Field Probes," *Appl. Phys. Lett.*, **68**, 2924, (1996).
7. Q. Wu and X.-C. Zhang, "Ultrafast Electro-Optic Field Sensors," *Appl. Phys. Lett.*, **68**, 1604 (1996).
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9. X.-C. Zhang, "Generation and Detection of Terahertz Electromagnetic Pulses from Semiconductors with Femtosecond Optics," *J. Luminescence*, Jan. 25, (1996).
10. Q. Wu and X.-C. Zhang, "Electro-Optic Sampling of Freely Propagating THz Fields," *Optics & Quantum Electronics,* in press, (1996).
11. Z.G. Lu, Q.Wu, and X.-C. Zhang, "New Ultrafast Field Sensors," WuLi (Physics), to be published, (1996).
12. Q. Wu, T.D. Hewitt, and X.-C. Zhang, "Electro-Optic Imaging of Terahertz Beams," submitted to *Appl. Phys. Lett.*, (1996).
13. M. Li, F. G. Sun and X.-C. Zhang, "Generation and Propagation of Coherent Sub-millimeter-Waves from Semiconductors," Acta Optica Sinica, **16**, 403, (1996).

Honors/Awards:

1996 Early Career Award, Rensselaer Polytechnic Institute

1995 CAREER award, National Science Foundation (previous NSF-NYI)

1995 Cottrel Scholar, Research Corporation

An U.S. patent which was supported by a previous AFOSR. "Microwave Radiation Source," X.-C. Zhang and D.H. Auston, U.S. patent No 5,420,595, (1995) (see the attached patent paper). We also wrote a patent disclosure, entitled" Electro-optical sensing apparatus and method for characterizing free-space electromagnetic radiation." by X.-C. Zhang, Qi Wu, and L. Libelo on May 28, 1996.

New Discoveries:

We reported our recent study of ultrafast electro-optic field sensors for the coherent measurement of freely-propagating subpicosecond pulsed electromagnetic waves (THz beams). The sensitivity and bandwidth of these electro-optic sensors are comparable with the conventional ultrafast photoconductive dipole antennas. The simplicity of the detection geometry and capability of optical parallel processing make these sensors suitable for real-time 2-D subpicosecond far-infrared imaging.

We reported on a novel electro-optic sampling system for real-time terahertz (THz) imaging applications. By illuminating a 6x8 mm^2 ZnTe crystal with a 300 μW optical time-sampling beam and detecting the beam with a digital CCD camera, we achieved time-resolved images of pulsed far-infrared radiation emitted from an unbiased GaAs wafer. At the focal point of the peak far-infrared field, the THz beam diameter is approximately 0.75 mm (FWHM). The temporal and spatial resolution of this imaging system are mainly limited by the laser pulse duration and the diffraction limit of the THz beam, respectively. A real-time measurement of 38 frame/second with 288x384 pixels imaging has been demonstrated.

We reported the measurement of the dynamics of free-space electro-optic field sensors for pulsed electromagnetic wave radiation. With an optical probe power spanning 6 decades of linearity and excellent signal-to-noise ratio, it is feasible to convert a far-infrared 2-D image into an optical 2-D image. A simple estimation indicates that 100 mW of optical probe power can achieve an image of 256x256 pixels with a 50 pA signal current per pixel and a SNR > 200. We also present a comparison measurement of an ultrafast photoconductive antenna and an electro-optic sensor crystal.

We reported the recent measurement and analysis of the transmitted and pseudo-reflected optically induced THz beams emitted from a semiconductor wafer under femtosecond laser illumination, where the static electric field is either parallel or perpendicular to the surface. In general the amplitude of the transmitted THz field is different from that of pseudo-reflected THz field, except at the Brewster angle.

We have tested photosensitivity, bandwidth, and device performance between regular GaAs and low-temperature grown GaAs as photoconductor for THz measurement. Antennas, based on commercially available GaAs as a photoconductor with a sub-nanosecond photocarrier lifetime, have been used to detect sub-picosecond free-space electromagnetic radiation (THz pulses). At low optical gating intensities (≤ 1 mW/100

μm^2) GaAs based antennas exhibit a higher responsivity and signal-to-noise ratio than typical antennas based on radiation-damaged silicon-on-sapphire. We found that a long carrier lifetime GaAs material (ns carrier lifetime) can be used to measure subpicosecond THz beam. The sensitivity of the antenna fabricated by regular GaAs is several hundreds times better than radiation-damaged silicon-on-sapphire at low optical power. It will be great impact on antenna array structure.

We demonstrated that free-space electro-optic sampling is an alternative method for the characterization of freely propagating terahertz beams with subpicosecond temporal resolution. In contrast to resonant photoconductive dipole antennas, free-space electro-optic sampling via the linear electro-optic effect (Pockels effect) offers a flat frequency response over an ultrawide bandwidth and the potential for a simple cross-correlation signal of the terahertz and optical pulses.

We reported our measurements of the broadband detection capability of co-propagating electro-optic ZnTe field detectors for the characterization of free-space pulsed electromagnetic radiation. To demonstrate ultrawide detection bandwidth, radiation from both gigahertz and terahertz bandwidth pulsed microwave sources has been characterized. The high frequency limitation of the sensor is the first TO phonon resonance (5.31 THz). The ultrashort temporal resolution is demonstrated by the detection of a 177 fs (FWHM) pulse generated via THz optical rectification in <111> GaAs.

Free-Space Electro-Optic Samplers

Electro-optic (EO) sampler can be used to characterize freely propagating pulsed electromagnetic radiation. This sampler is the extension of the conventional electro-optic sampler for local field characterization into free-space application. The preliminary study on these samplers has demonstrated diffraction-limited spatial resolution, femtosecond temporal resolution, THz bandwidth, and mV/cm field detectability. The measured sensitivity (1×10^{-17} W/$\sqrt{\text{Hz}}$) and bandwidth (4 THz) of these electro-optic probes are comparable or better than the conventional far-infrared coherent detection methods. Fig. 1 schematically illustrates the experimental setup of free-space counter-propagating electro-optic sampler. A cw mode-locked Ti:sapphire laser is the optical source. Several different emitters have been tested, including photoconductive tapped antennas (transient current source), unbiased <100> GaAs wafers (transient photovoltaic source), and a <111> GaAs wafer with normal incidence (optical rectification source). The radiation sensor is a $LiTaO_3$ crystal plate (100 μm thick) sandwiched between two fused silica prisms. Fig. 3

plots the temporal EO signal from an unbiased <100> GaAs wafer with Brewster angle incidence.

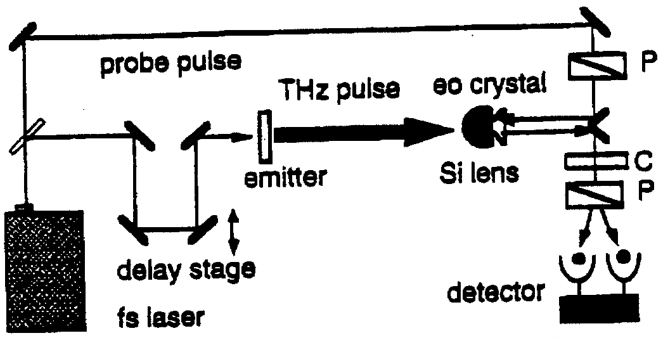


Fig. 1: A counter-propagating sampler.

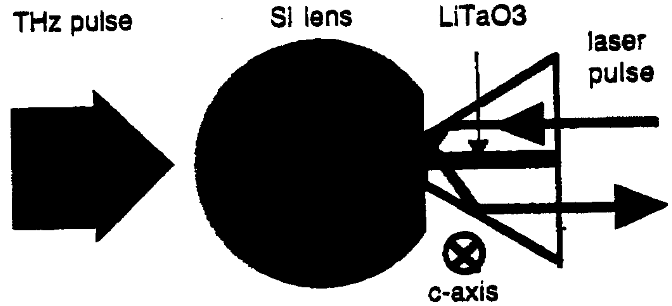


Fig. 2: A $LiTaO_3$ crystal sandwiched between two fused silica prisms.

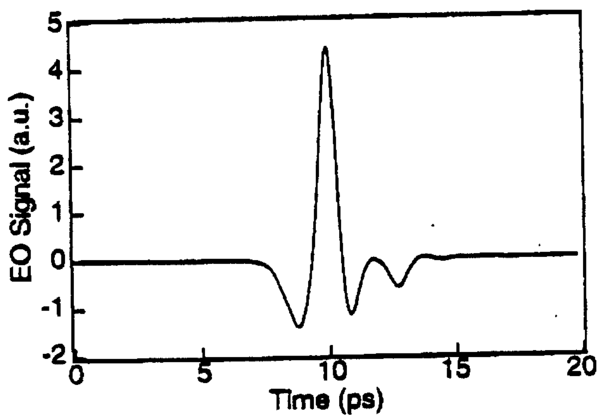


Fig. 3: EO signal measured by using the counter-propagating sampler.

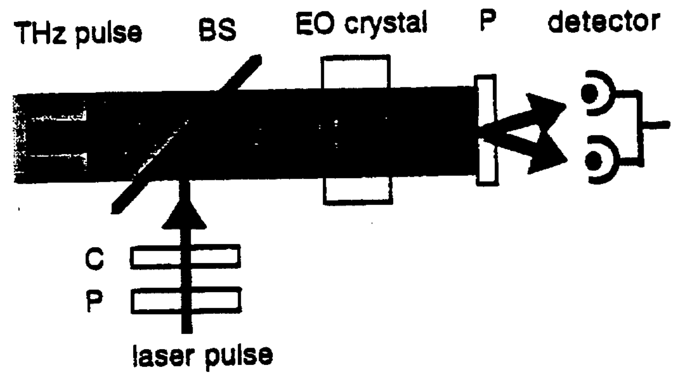


Fig. 4: Co-propagating EO sampler.

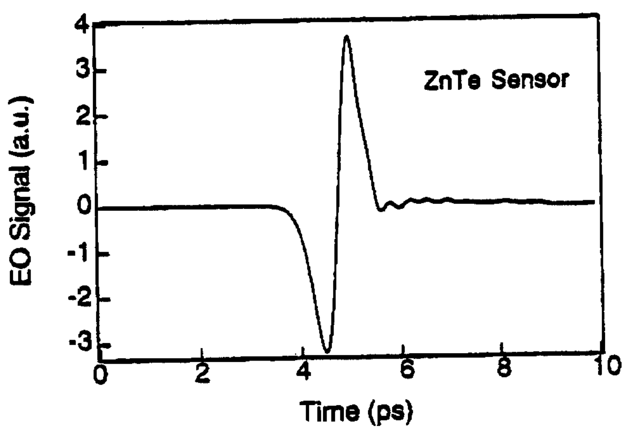


Fig. 5: Temporal EO signal measured by using the co-propagating geometry.

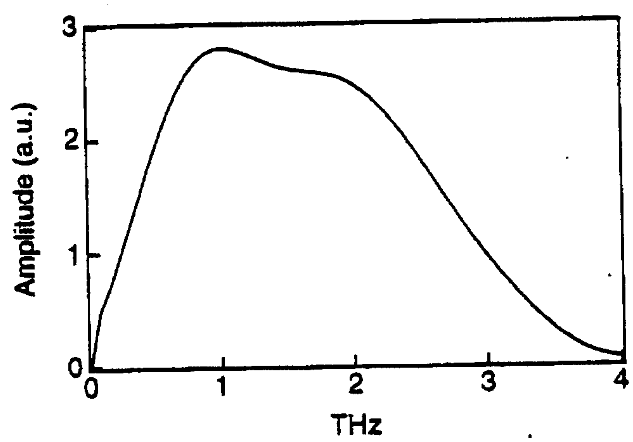


Fig. 6: Amplitude spectrum of a temporal signal from optical rectification.

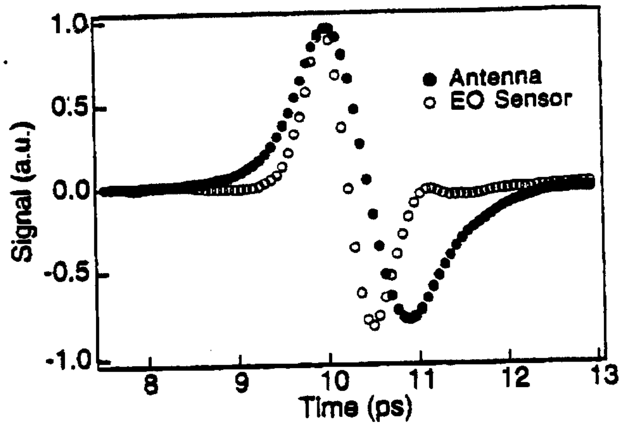


Fig. 7: Comparison of a photoconductive antenna and an EO sensor.

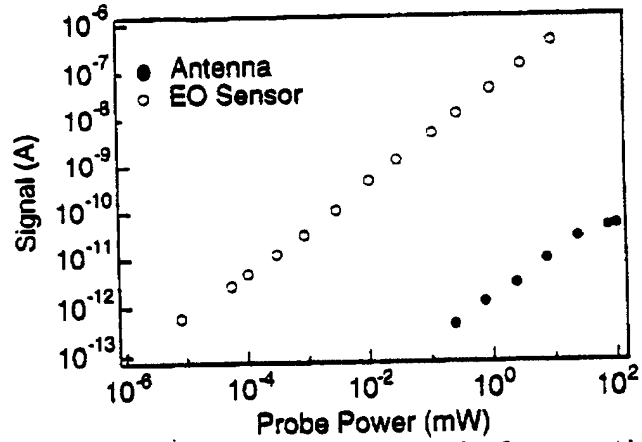


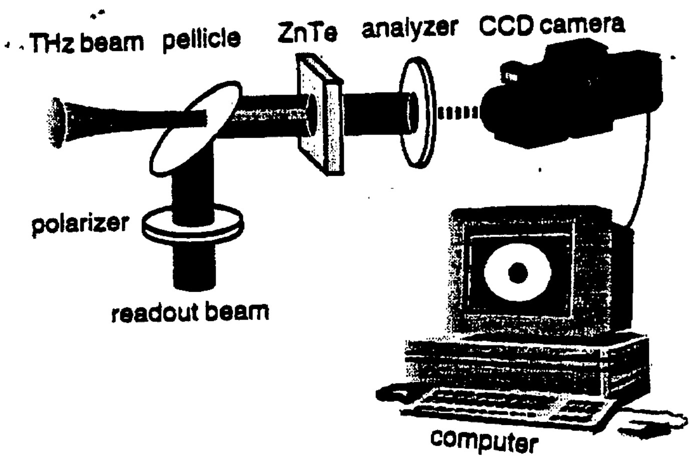
Fig. 8: EO sensor uses much less optical gating power (at least by 4 orders).

Detection sensitivity can be significantly improved by increasing the interaction length of pulsed field and optical probe beam in the electro-optic crystal. Fig 4 is a schematic illustration of co-propagating electro-optic sampling. A 1.5 mm thick <110> oriented ZnTe crystal is the probe head. Fig. 5 plots the temporal waveform of electro-optic signal from an unbiased <100> GaAs wafer in expended scale. Signal-to-noise is better than 10000:1 even with an unfocused radiation on the ZnTe crystal. The ring after the main peak is due to the dispersive contribution by the first TO phonon resonance in ZnTe. We have tested this sensor with an extremely short microwave pulse by using a <111> GaAs emitter with a normal incidence and a thin ZnTe (250 μm). The radiation is generated by THz optical rectification, the radiation pulse is limited by the optical pulse duration and dispersion in the material. The frequency spectrum extends to 4 THz, as shown in Fig. 6.

Figure 7 shows a comparison of normalized waveforms measured by using a radiation-damaged silicon-on-sapphire photoconductive antenna and a ZnTe electro-optic sensor. The pulsed far infrared emitter is fixed during the test with a probe power of 70 mW for the antenna and 2 μW for the sensor, respectively. Fig. 8 is a plot of measured signal from the antenna and the electro-optic sensor versus optical probe power. The electro-optic sensor uses much less optical gating power (at least by 4 orders) than that for antenna.

Electro-Optic Imaging of THz Beams

We developed an alternative method for real-time terahertz (THz) imaging applications. By illuminating an electro-optic crystal with a THz beam and an optical readout beam, then detecting the optical beam with a linear diode array or a CCD camera, we achieved time-resolved 1D or 2D images of pulsed far-infrared radiation. The temporal and spatial resolution of this imaging system are mainly limited by the laser pulse duration and the diffraction limit of the THz beam, respectively.



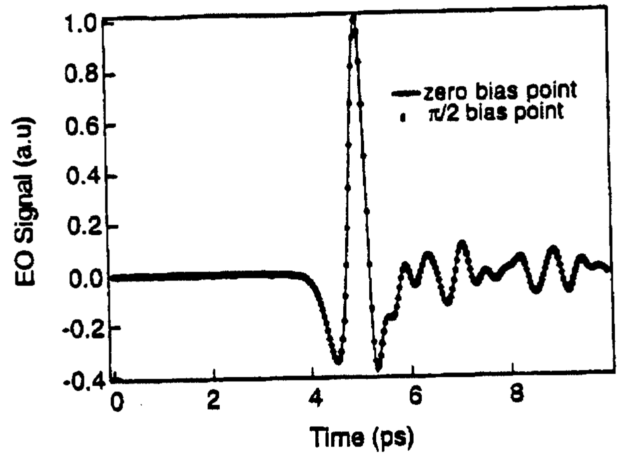
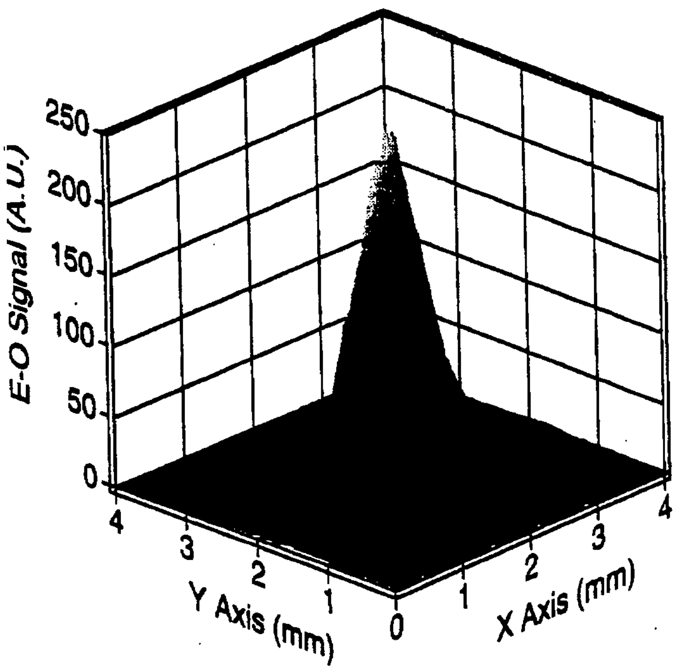


Fig. 9: Setup for the conversion of a THz image into an optical image.

Fig. 10: THz radiation under conditions of zero and quarter-wave optical bias.

Fig. 9 schematically illustrates the experimental arrangement for free-space electro-optic THz imaging. The basic operating principles and experimental details of collinear electro-optic sampling have been described previously. Fundamentally, this system is based on the linear Pockels' effect in electro-optic crystals where a pulsed microwave signal acts as a transient bias to induce a transient polarization in the sensor crystal. This polarization induces a birefringence which is then probed by a synchronously pulsed laser beam, and finally converted to an optical amplitude modulation via optical polarization analysis. The laser source is a Ti:sapphire laser with a pulse duration less than 50 fs, and an unbiased GaAs wafer is used to generate pulsed electromagnetic radiation. Parabolic mirrors were used to focus the THz radiation on a 0.9 mm thick, 6x8 mm^2 <110> oriented ZnTe crystal. An optical readout beam with a diameter larger than that of the THz beam probes the electric field distribution within the crystal via the Pockels effect. The 2-D field distribution in the sensor crystal is converted into a 2-D optical intensity distribution after the readout beam passes through a crossed polarizer, and the optical image is then recorded by a linear diode array or a digital CCD camera. No focusing optical element was used between the sensor and the camera. There are no moving parts in the system except for the variable time delay stage.

We used a pair of crossed polarizers with the ZnTe crystal in between for a zero optical bias operation in order to provide enhanced modulation depth. The peak signal modulation depth achieved with crossed polarizers was 7% as compared to 0.1% with quarter-wave bias. Since the induced phase change is still much smaller than π, we expect the readout light modulation will still be linearly proportional to the THz electric field. To investigate the severity of the distortion caused by non-quarter-wave bias, a comparison between standard balanced detection (quarter-wave bias) and crossed-polarizer technique was made, where the readout beam focused to 0.1 mm on the ZnTe crystal. The normalized waveforms obtained with two different methods turned out to be almost identical, as shown in Fig. 10. The crossed-polarizer geometry thus provides the best trade-off between SNR and linearity for detection with CCD camera.



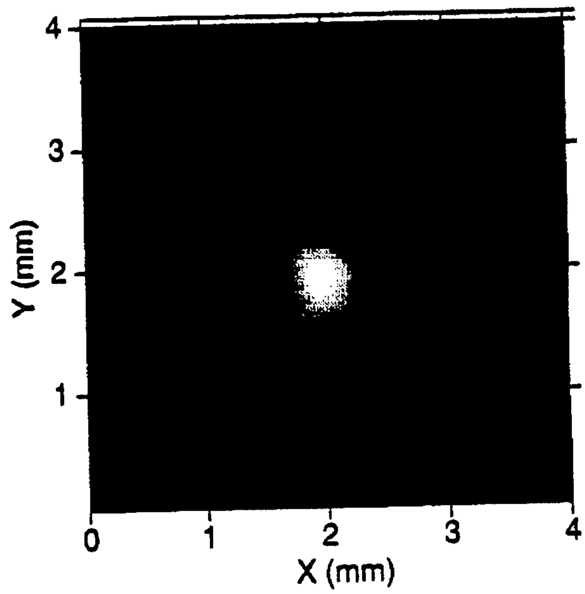


Fig. 11: A typical image of the peak field distribution of a focused THz beam.

Fig. 12: 2D display (x-y) of Fig. 11

The largest photomodulation, occurring at the focal point of the THz beam, was about 7%. By chopping the THz beam, the change in optically recorded gray levels caused by this modulation of the THz signal was observed on the monitor in real-time. The temporal resolution is about 50 fs. Current transfer frame rate is 38 frames per second, and it can reach to 190 frames per second. The signal also can be greatly enhanced when the background was numerically subtracted. Fig. 11 is a 3-D plot of the spatial distribution of the peak THz field near the focal point (background light is removed). Only 4x4 mm^2 out of the 8.4x6.3 mm^2 total area are plotted in the figure. The measured cross section (FWHM) of the field, as shown in Fig. 12, is slightly elliptical with long and short axes of 0.79 m m and 0.75 mm, respectively.

We have demonstrated the real-time, 2-D free-space electro-optic imaging of THz beams. We used a ZnTe crystal and a digital CCD camera to convert a far-infrared image into an optical image with diffraction-limited spatial resolution and femtosecond temporal resolution. This imaging system offers THz bandwidth and mV/cm field detectability.

The parallel optical processing provides the ability to measure the 2-D spatially distributed phase and amplitude information of THz radiation in a true real-time mode (38 frames per second with 384x288 pixels).

Rensselaer Polytechnic Institute

Cost Estimate Summary: Two Years
Period: (11/1/96 - 10/31/98)

Proposal No. 464-96-057K, Revised 9/18/96

	Year One	Year Two	Total
PERSONNEL			
Principal Investigator (S. Komisar) academic - 9 mos @ 7.5%	$4,371	$4,503	$8,874
Graduate Research Assistant(s) tuition - 15 credits (1,1)	8,663	9,180	17,843
academic - 9 mos @ 50% (1,1)	10,500	10,814	21,314
summer - 3 mos @ 100% (1,1)	3,500	3,605	7,105
Undergraduate Assistance-URP	750	750	1,500
Clerical Assistance - as required	1,434	1,475	2,909
TOTAL PERSONNEL PAYMENTS	**$29,218**	**$30,327**	**$59,545**
FRINGE BENEFITS @ 31%*	1,800	1,853	3,653
EQUIPMENT+			
Pilot Plant	3,500	350	3,850
TRAVEL			
Domestic: 100 round trips RPI/Albany County Airport	465	465	930
Attend conference to present results	350	1,000	1,350
OTHER DIRECT COSTS			
Materials and Supplies	3,500	3,500	7,000
Communications	350	350	700
TOTAL DIRECT COSTS	**$39,183**	**$37,845**	**$77,028**
INDIRECT COSTS @ 26%*	6,830	7,167	13,997
TOTAL PROJECT COSTS	**$46,013**	**$45,012**	**$91,025**
COST SHARING:			
5% of PI's AY chargeout & related fringe benefits & indirect costs	(4,809)	(4,956)	(9,765)
Tuition - 6 Credits	(3,465)	(3,672)	(7,137)
TOTAL FUNDS REQUESTED	**$37,739**	**$36,384**	**$74,123**

*See Attachment

+Equipment listed cannot be acquired with Rensselaer or other private resources due to academic program commitments.